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EQUIPMENT FOR MEASURING THE REFLECTIVE AND TRANSMISSIVE PROPERTIES OF DIFFUSING MEDIA

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ABSTRACT

The construction and operation of equipment is described for studies of the diffusion and absorption of light by materials such as textiles, papers, paints, enamels, and other diffusing media for which measurements of color, gloss, transparency or optical density, hiding and tinting powers, or similar properties, are required. Means are provided for the precise control of the directional and spectral distributions of light incident on the sample and for measurement of the corresponding distributions of diffused light.

The equipment includes two separate illumination units, one for completely diffused illumination of the sample and the other for unidirectional illumination at any desired angle of incidence. Light reflected or transmitted by the sample under either type of illumination is measured for any desired direction of observation by visual photometric or spectrophotometric methods.

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I. INTRODUCTION

Many problems in diverse fields of science and industry call for studies of the diffusion¹ and absorption of light by optically non-homogeneous materials such as textiles, papers, paints, ceramic bodies, illumination glassware, photographic plates or films, and liquid suspensions of finely divided particles. The distribution of the diffused light, with respect to direction and wave length, is determined by the composition, structure, and form of the diffusing medium and by the directional and spectral distribution of the in-

¹ The word diffusion is employed herein to cover a multitude of refractions, reflections, diffractions, and Rayleigh scattering, taking place at the surfaces or within the body of the diffusing medium, by virtue of which there is a general directional redistribution of the incident light.

cident light. In some problems the immediate objective is the establishment of definite relations between elements of composition or structure and the observed distributions of light. In other cases the nature of the medium itself is a secondary consideration, and we are concerned chiefly with the numerical description of properties such as the color, gloss, and surface texture of fabrics, papers, and painted or enameled surfaces, the hiding and tinting powers of paints and enamels, the transparency and optical density of printing papers, tracing papers, or photographic films, and other characteristics of similar nature for which optical methods of specification are required.

In an analysis of the color of a given material we deal chiefly with the spectral distribution of light incident on the sample and with the change in this distribution brought about by the sample (absorptive properties). The physical factors determining the appearance of gloss, on the other hand, are to be found chiefly in the directional distributions of the incident and diffused light (diffusive properties). It is common experience, however, that the color of a material often varies markedly with the directional distribution of the incident light or with the particular direction chosen for the observations. Likewise, in the derivation of any adequate specification for gloss we cannot ignore the effect of the light distributions with respect to wave length. Gloss is dependent to a large degree on the absorptive properties of the material. Hence, diffusion and absorption, involving directions and wave lengths, are inextricably interrelated in the problems of colorimetry and glossimetry.

In present colorimetric practice there is not universal agreement in regard to directional conditions, or sets of such conditions, which should be adopted for various purposes of colorimetry.² Little quantitative information is available on the magnitude of color differences to be encountered under varying directional conditions of illumination and observation. The problem becomes most acute perhaps in the colorimetry of textile materials, because of the great range of colors, variable surface texture, and body structure presented by this class of materials.

In the evaluation of the hiding and tinting powers of paints and enamels we deal with materials for which certain elements of structure may be known, such as the size distribution, shape, or concentration of the pigment particles, along with the compositions and the refractive and absorptive properties of individual particles and the embedding medium. Under suitably prescribed conditions of illumination and observation the problem may consist (1) in the development of numerical expressions for hiding and tinting powers, and (2) in the relation of these properties to certain characteristic structural parameters, so that the performance of the material may be better understood and its behavior predicted as the parameters are changed. Such problems are fundamental in the paint and enamel industries.

The choice of the conditions of illumination and observation for photographic density measurements has long been the subject of controversy in quantitative photographic testing and research.

² See table 1 for the single directional condition adopted by international agreement.

Density values depend on the directional and spectral distributions of light employed in the measurements. Different densities may be defined and measured and are useful for various purposes.

Other illustrative problems include the measurement of transparency and printing opacity of papers, multiple reflection methods for precision colorimetry of nearly white materials, specifications of surface finish or smoothness as indicated by reflective or polarizing properties, and the development and specification of material standards for use in colorimetry and photometry.

It is the purpose of this paper to describe equipment which has been assembled for investigations such as indicated above. Means are provided for controlling the directional and spectral distributions of light projected on the sample and for measuring the corresponding distributions of diffused light. Various diffusive and absorptive properties derived from such measurements provide the physical basis for a rational treatment of the suggested problems, but specific applications of the equipment are not included in the scope of the present paper.

II. FIXED CONDITIONS FOR THE MEASUREMENTS

In the most general condition of illumination on the sample the distribution of intensity and polarization in the incident light may vary continuously or discontinuously in any complex manner with direction of incidence and with wave length. Some investigations may call for a particular form of sample or for some special condition of illumination. Most purposes will be adequately served, however, if the form of the sample and the available types of illumination are limited to a few fixed, or standard, reproducible conditions under which the diffusive and absorptive properties are defined and measured.

The following conditions are established to a close approximation by the construction of the apparatus herein described:

(1) *The sample* is in the form of a slab of uniform thickness, composition, and structure, throughout its entire lateral extent. This extent is such, relative to the thickness and point of observation (S, fig. 1), that edge effects are always negligible.

(2) *The conditions of illumination* are constant over the entire extent of the sample, so that various coefficients of reflection and transmission may all be referred to unit areas of the reflecting and transmitting surfaces.

Each coefficient is a ratio of light reflected or transmitted per unit area to light incident per unit area, and includes in its definition specific directional and spectral conditions of illumination and observation. The various coefficients are conveniently classified into groups, each group corresponding respectively to some one definitely specified condition of illumination³ and including various conditions of observation. In table 1 the conditions of illumination are divided into two main groups, corresponding, respectively, to restrictions imposed on the directional and spectral distributions of incident light.

³ Some coefficients of reflection, their interrelation and measurement, have been defined and discussed by the author in B.S. J. Research 1, 29(1928); RP3. Further definitions of this kind may be taken up as needed in future work.

(3) *Unidirectional illumination*.—The condition of illumination is defined as unidirectional when the incident light is distributed over a small range of directions, so small that any further reduction in range would have no appreciable effect on the measurements to be made. In the present equipment the source is such that throughout the lateral extent of the unidirectional beam the polarization is nil and the intensity and its spectral distribution are independent of the direction of incidence on the sample.

(4) *Completely diffused illumination*.—The illumination is completely diffused when it is obtained by the superposition of unidirectional incident beams, each of which fulfils conditions (2) and (3) as specified above, and all together cover continuously the complete range of incidence directions represented by the solid angle of 2π with vertex at any point on the illuminated surface.

The diffusive and absorptive properties for any type of multi-directional or partially diffused illumination between the two extreme

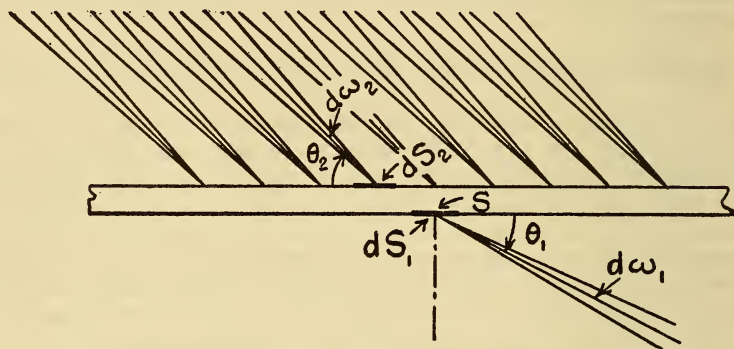


FIGURE 1.—Diagram of unidirectional incident beam.

types here defined may always be derived by addition of effects as observed separately for various modes of unidirectional illumination. No particular type of partially diffused illumination appears at present to be of sufficient practical interest to be classed as a standard condition.

The unidirectional and completely diffused types of illumination are of particular interest as standard conditions because of the reciprocal relations which have been shown to exist between certain groups of reflection and transmission coefficients. These relations have been discussed at length in other publications⁴ and are of considerable importance in the applications of the equipment.

(5) *Homogeneous illumination*.—In the above specification of directional conditions the relative spectral distribution of incident light remained arbitrary. When the spectral distribution of incident light covers a small range of wave lengths, so small that further reduction in range would have no appreciable effect on the measurements, then the illumination is defined as homogeneous with respect to wave length.

⁴ Meslin, *Ann. de Phys.* [9] 1, 297 (1914). McNicholas, *BS J. Research*, 1, 29 (1928) RP3; Boutaric, *Rev. d'Opt.*, 10, 485, (1931).

The reciprocal relations have been defined between coefficients of reflection only. Corresponding relations apply equally well, however, between the corresponding coefficients of transmission.

(6) *Composite illumination*, heterogeneous in wave length. In analogy with the condition of partially diffused illumination the diffusive and absorptive properties for any special type of composite illumination might be derived by addition of effects observed separately for the different homogeneous components. The extensive observations and computations involved are often avoided, however, by making observations directly under the given spectral distribution of incident light. Standard conditions of composite illumination for colorimetric purposes are indicated in table 1.

TABLE 1.—*Conditions of illumination commonly employed in reflectometry and transmissometry*

Directional conditions		Spectral conditions	
Type	Special cases	Type	Special cases
Unidirectional.....	Incidence at 0°..... Incidence at 45° ¹	Homogeneous with respect to wave length.	Any wave length in visible spectrum.
Partially diffused.....	No special case generally employed or of particular interest.	Composite, or heterogeneous with respect to wave length.	Illuminant A. ¹ Illuminant B. ¹ Illuminant C. ¹
Completely diffused....	Frequently used in photometry and spectro-photometry.	Equal energy at all wave lengths.	Not easily realized in practice.

¹ Adopted as standard conditions in colorimetry by international agreement. Proceedings of the 8th session, Comm. Int. l'Eclairage, Cambridge, p. 19 (1931). Unidirectional illumination at 45° incidence adopted for reflectance measurements only. Illuminants A, B, and C approximate closely to the gas-filled lamp, average noon sunlight, and average daylight, respectively.

III. DESCRIPTION OF APPARATUS

A plan of the assembled equipment is shown in figure 2. Many details of the construction and operation of different units of the assembly, not included in the text, are given in the legends to the various figures.

The two fixed directional conditions of illumination, as defined above, are respectively realized to a sufficient approximation by the construction of two separate illumination units, one for unidirectional and the other for completely diffused illumination of the sample. These units contain incandescent-filament lamps emitting light covering a continuous extension in wave length over the entire range (visible spectrum) required for the intended applications of the equipment. For a given directional condition of illumination the desired control of the relative spectral distribution of incident light is effected by use of selective light filters of various kinds, including, for homogeneous illumination, the highly selective dispersion system of a spectrometer. Excluding the case of strongly fluorescent diffusing media, in which there is an appreciable transformation of light from a given wave length to other wave lengths, it is well known that the overall intensity gradient along any ray path from the source through the sample to the light-sensitive receiver is independent of the sequence in position along that path of selective light filters of any kind. Consequently, the desired control of the spectral distribution of incident light is accomplished effectively and most conveniently in the

present equipment by placing the selective light filter between the sample and the receiver, instead of attempting a direct control of the illumination itself. This is the usual procedure in photometry and spectrophotometry when a unidirectional observing beam is employed.⁵

The complete assembly of apparatus consists essentially of the two illumination units with sample holders, a ventilation system, and the photometric equipment, which contains the selective light filters for effective control of the spectral conditions of illumination on the sample. The photometric equipment is stationary and the sample is always observed in a fixed horizontal direction. To provide for variations in the directions of illumination or observation the observed surface of the sample and the positions of the light sources may be oriented differently with respect to the fixed direction of observation. A part of the photometric equipment (comparator and sector-disk

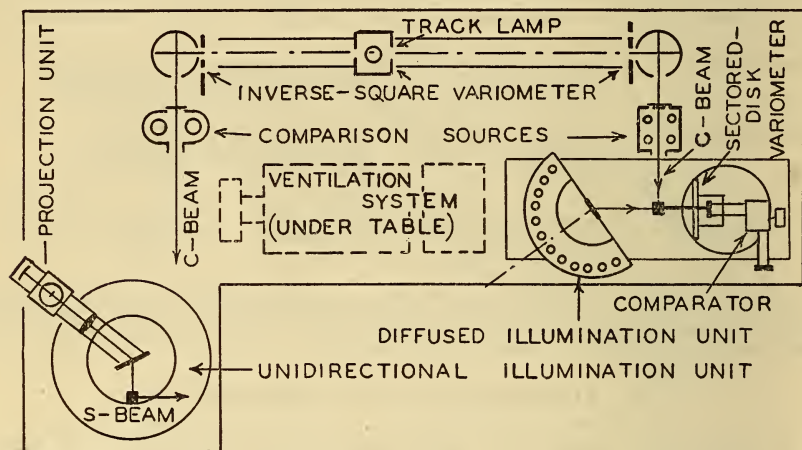


FIGURE 2.—*Plan of assembled equipment.*

variometer, fig. 8) is mounted on a single detachable base-plate and may be transferred readily from one illumination unit to the other.

The intensity and polarization of an unidirectional homogeneous or composite beam of light, as received from the sample under either type of illumination, is measured by ordinary visual photometric procedure, using either the equality-of-brightness or minimum-flicker methods of photometry.

1. UNIDIRECTIONAL ILLUMINATION UNIT

The construction of the unidirectional illumination unit is shown in figures 3 and 4. In each figure the source and sample are in proper position for photometric measurements on the sample by transmitted light.

The source (1) is a 1,000-watt projection lamp with its coiled filaments centered on the common axis, and lying in the common principal focal plane, of a plano-convex lens (11) and concave mirror (13),

⁵ Equipment in which the selective light filter is placed between the source and sample is described, for certain limited applications, by Gibson (J. Opt. Soc. Am. and Rev. Sci. Instr., **18**, 166 (1929); **21**, 144 (1931). This method is also incorporated in the photoelectric spectro photometer of Hardy (J. Opt. Soc. Am. **24**, 162 (1934)).

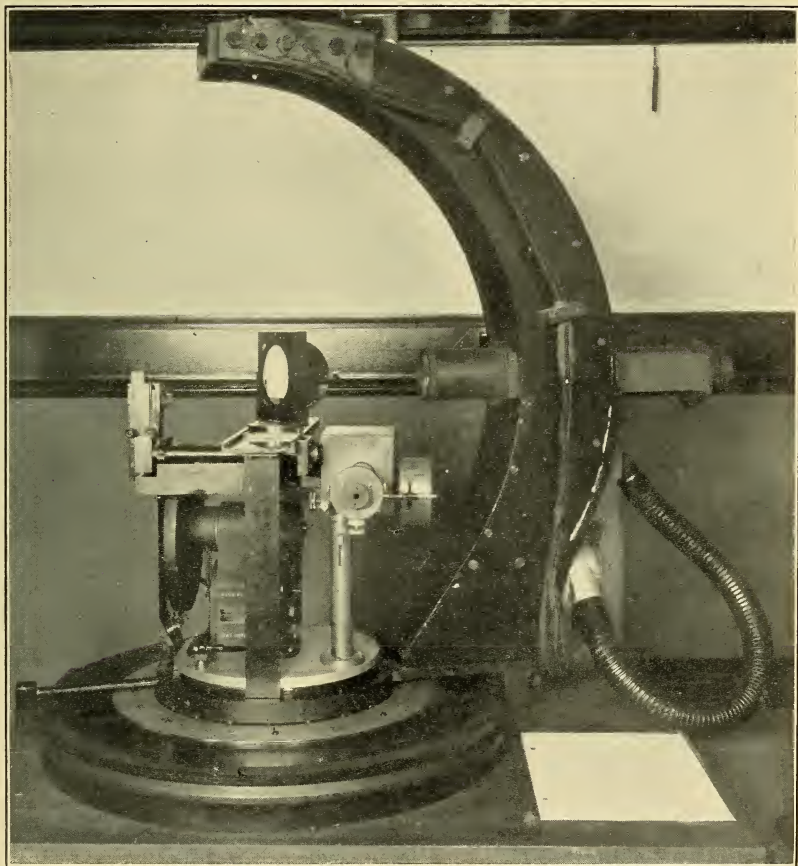


FIGURE 3.—*Apparatus for reflection and transmission measurements with uni-directional illumination of the sample.*

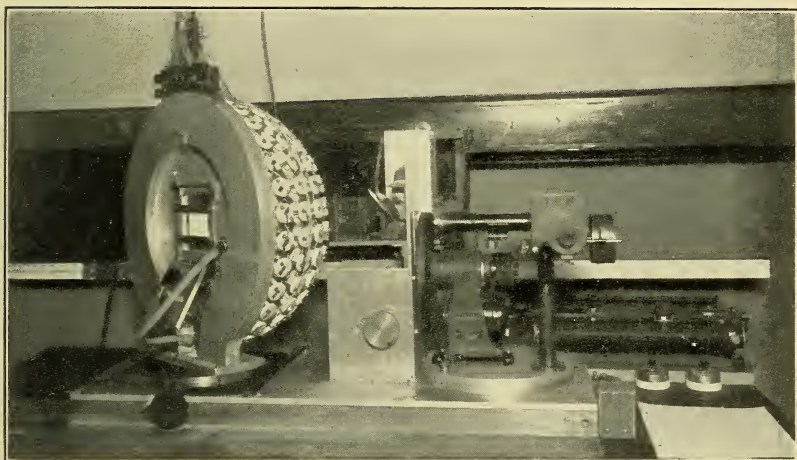


FIGURE 5.—*Apparatus for reflection and transmission measurements with completely diffused illumination of the sample.*

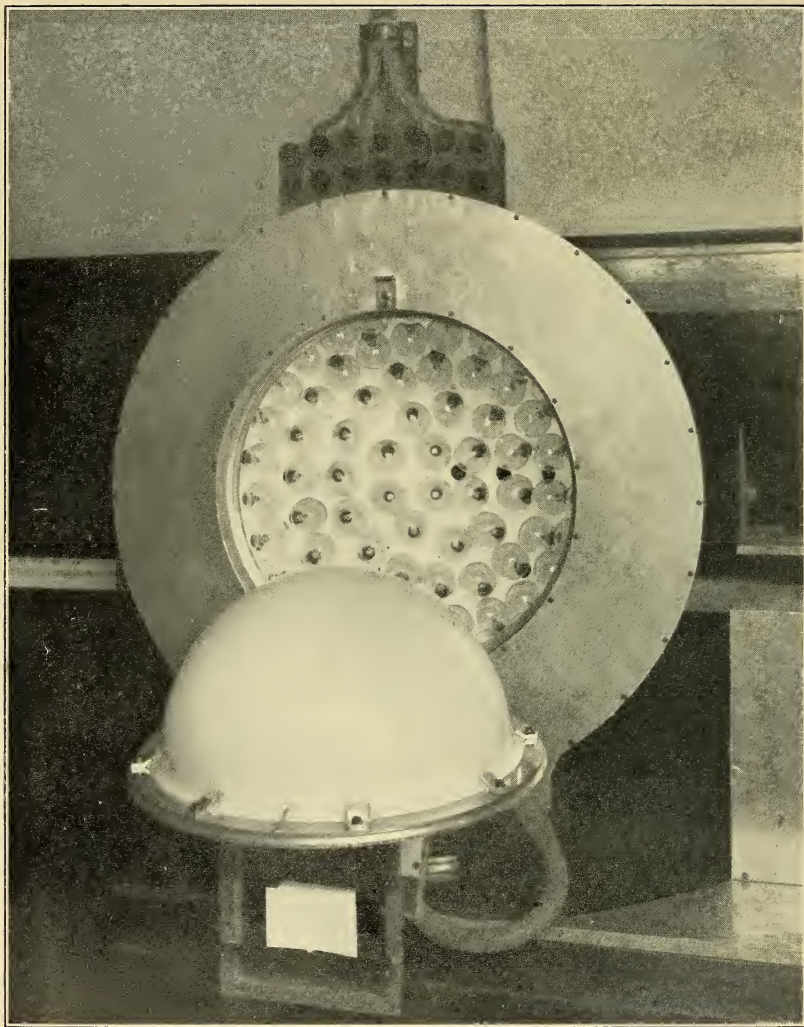


FIGURE 6.—Hemisphere source for completely diffused illumination, showing opened door carrying milk-glass hemisphere and arrangement of lamps on white-lined steel hemisphere.

so that an intense unidirectional beam is thus defined and projected toward the center of the sample. A small blower (9) delivers a strong blast of air directly against the base of the lamp, a provision for cooling which is necessary in order to operate this lamp continuously in the small blackened box (3). The lamp box and blower, together with lens and mirror supports, are all mounted as a unit on a rigid frame (16). This unit is in turn supported by the large arc-shaped frame (19) and is free to slide on the vertical circular track (20), which is centered at the center of the sample. The entire projection unit may be moved and clamped at any desired position on the circular track, so that the unidirectional beam is directed onto the sample at any desired angle from the horizontal to the vertical.

The arc-shaped support for this projection unit is mounted on a heavy circular iron base (24) so that the source may be rotated through 360° about a vertical axis passing through the centers of the base and sample.

The mounting of the sample permits of three degrees of rotational freedom. It may be rotated through 360° about a vertical axis and through 180° about a horizontal axis. Both axes pass through the center of the sample with the horizontal axis lying in the plane of the illuminated surface. In addition, the sample may be rotated in its own plane about an axis through its center and normal to its surface. Circular scales indicate the amounts of these rotations.

In the figures and the text the fixed horizontal unidirectional beam of light, proceeding from the sample to the photometric system, is always designated as the S-beam. The complete sample holder (42) slides between guides on a horizontal table (40), the direction of motion being perpendicular to the direction of observation (direction of S-beam). A transmission or reflectance standard (41) is mounted on the same table, so that the sample may be moved quickly and conveniently from the path of the incident beam and the comparison standard substituted in its place. The standard is held in a fixed position on its holder. Its reflective or transmissive properties are either known for various positions of the source, or the source may always be brought to some specified position, such as 0° incidence, when the comparison standard is being observed.

The central raised portion of the circular base plate (24) carries a part of the photometric equipment. This equipment is described in section III along with other parts of the photometric system shown inclosed in box (46).

The three degrees of freedom of the sample, with the two degrees of freedom of the source, permit combinations of all desired directions of incidence and observation for any sample. In this connection the Helmholtz reciprocity law⁶ may be applied to great advantage, because every measurement made with a particular combination of directions of incidence and observation has its reciprocal interpretation as a measurement for reversed directions of incidence and observation.

With the 1,000-watt lamp operating at normal voltage, and using a collimating lens (11) of 20 cm focus, the brightness of a magnesium carbonate block for 0° incidence and 45° observation is approximately 5.8 lamberts.

In the measurement of the directional distribution of light over a range of directions through which the intensity gradient is very steep

⁶ See footnote 4.

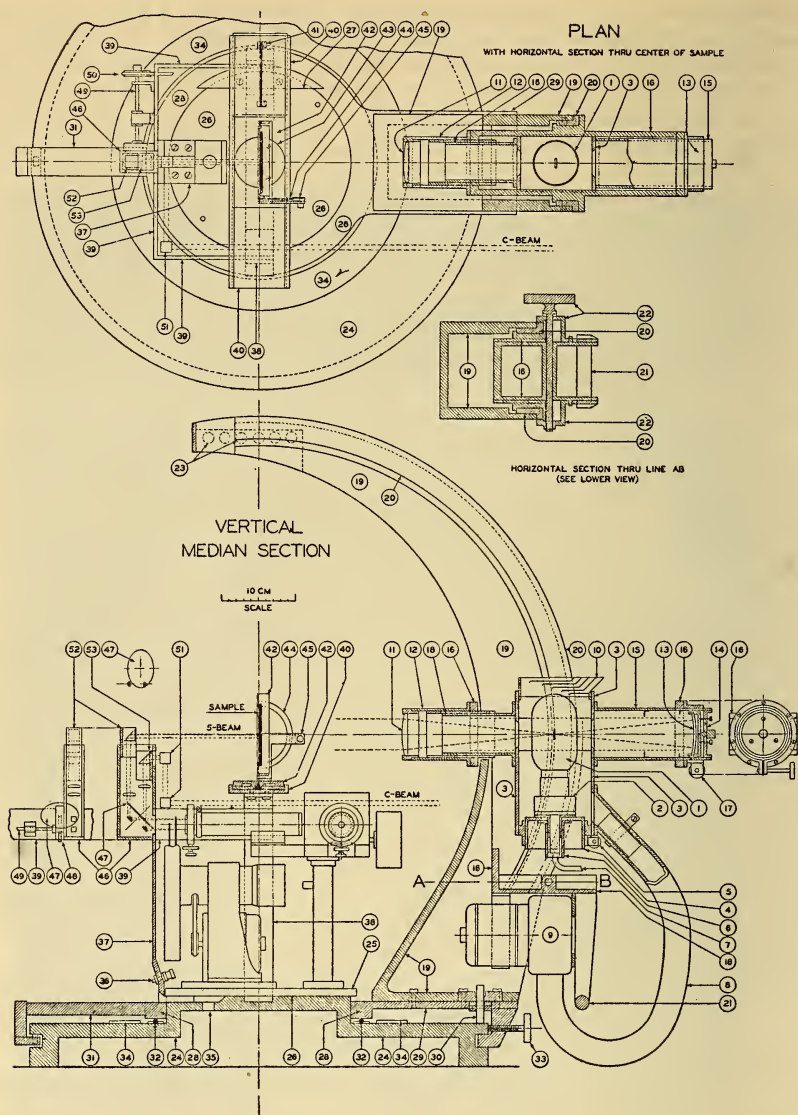


FIGURE 4.—Construction of unidirectional illumination unit.

1. Gas-filled tungsten-filament projection lamp, 110 volts, 1,000 watts. 2. Mogul base lamp receptacle; upper part of porcelain body cut away, thus exposing metal parts for better cooling. 3. Blackened lamp box. 4, 5, 6. Vertical, lateral, and rotational adjustments of lamp. 7. Current leads through bakelite bushing. 8, 9. Flexible metal tube and air blower for forced ventilation of lamp box. 10. Removable top of lamp box, obstructing passage of light but permitting free egress of air. 11. Plano-convex lens, focal length 20 cm, diameter 6 cm. Lens of 30 cm focus also provided. 12. Lens support held rigidly to frame (16). 13. Concave silvered-glass mirror, 20 cm focal length, centered on axis of lens at focal distance from plane of lamp filaments. 14. Support and adjustments for mirror holder. Mirror forms image of lamp filaments in space between coils. Intensity of collimated beam thereby increased 70 percent. 15. Mirror support mounted rigidly on lamp box. 16, 17. Brass frame supporting lamp box, lens, and mirror tubes, and ventilating blower. Loosening clamp (17) permits lamp box with mirror tube to be moved on frame parallel to axis of lens, thus adjusting plane of lamp filaments in focal plane of different lenses. Lenses from 20 to 30 cm focal length may be accommodated. 18. Telescoping tubes. 19. Aluminum frame supporting two arc-shaped brass guides (20), which form a vertical circular track having sample at center. 20. The brass frame (16), supporting entire projection unit, slides freely on circular track (20), keeping axis of lens pointing to center of sample. 21, 22. Handle and clamping device for projection unit. See section view through frame (19) along line AB. Circular scale (not shown) engraved on one arm of frame (19) gives position of source on circular track. 23. Terminals for current leads. 24. Cast-iron cir-

(reflection from glossy sample near the angle of specular reflection) it may be found that the incident beam no longer fulfills the condition for unidirectional illumination as prescribed in section II, condition (3). If so, the directional extent of the incident beam, and hence the resulting error in the intensity measurement, may be reduced by the use of a projecting lens of longer focus. Provision for such adjustment has been made, as explained in the legend to figure 4, items 16, 17, and 19. The directional extent of the observing beam is determined by the construction of the comparator (sec. III, 3, (a)) and is considerably less than that of the incident beam, so that the required condition is in this case readily fulfilled. These possible errors in the measurement of directional distributions are analogous to the slit-width errors well known in ordinary spectrophotometry, which arise from the use of a measuring beam containing too large an extension in wave length.

2. DIFFUSED ILLUMINATION UNIT

The construction of the source for completely diffused illumination is shown in figures 5, 6, and 7, with a detailed description of various parts in the legend to figure 7.

The illuminated plane surface of the sample forms a part of the base of a milk-glass hemisphere (19), the inner concave surface of which, as viewed from the position of the sample, is of uniform brightness over all its parts. This fully extended source of uniform brightness is obtained by direct illumination of the outer convex surface of the translucent hemisphere by means of a concentric hemispherical arrangement of one hundred and four 27 cp lamps (21). These lamps are uniformly distributed over the inner concave surface of a larger concentric steel hemisphere (20), with the axis of each lamp pointing toward the common center of the hemispheres. The lamp bases project through circular holes in the steel hemisphere and each lamp is supported with its receptacle on the outer surface. Approximately 7 percent of the total area of the inner surface of the steel hemisphere is taken up by the openings provided for the lamp bases; the remaining surface is covered with a double coating of white porcelain enamel (baked) over which a film of magnesium oxide is deposited. The white diffusely reflecting surface thus obtained considerably increases

cular base, 58 cm in diameter. Central raised part carries base plate (25). 25. Base plate carrying parts of photometric equipment which are transferable from one illumination unit to the other. See also figures 3, 5, and 8. This equipment is removed in upper plan view. 26. Flat upper surface of raised portion of base (24). 27. Guiding edge for base plate (25), permitting accurate alignment of photometric equipment on surface (26). See corresponding edge of base plate (25) in figure 8. 28. Circular guide ring with bearings as shown, and with two projecting arms, (29) and (31). Rotates about vertical axis through center of base. 29, 30. Arm-plate and ball-bearing roller supporting frame. (19). 31, 32. Balancing arm and ball-bearing race. 33, 34. Clamp for horizontal motion and circular scale. 35, 36. Hole in base and binding posts for detachable electrical connections to sectored-disk motor. 37, 38, 39. Supports for box (46), table (40), and other parts. 40. Table for support of sample and standard. Base plates of sample and standard holders slide between guides on edges of table top, so that sample and standard may be alternately brought into proper position for illumination and observation. 41. Holder for reflection or transmission standard. Position stationary on holder. 42. Holder for sample. Sample may be rotated about horizontal and vertical axes through its center and about axis perpendicular to its surface. 43. Horizontal circular scale. 44. Vertical semicircular scale. 45. Clamp and index. 46. Box containing prisms and lenses for directing light beams to the comparator. 47. Flicker disk, 4 cm in diameter, similar in construction to disk in figure 7, item (11). The three views show position of disk relative to light beams. 48. Disk mounted on shaft outside of box (46) and connected by bevel gear to shaft (49). Adjustment for disk in beams is provided. 49, 50. Shaft and pulley transmits motion to flicker disk. Pulley connected by belt to motor located under table. Other pulleys (not shown) guide belt down side of (38) and through raised part of base (24), between guiding edge (27) and rotating ring (28). Hence, belt line does not interfere with the insertion or removal of the photometric equipment mounted on base (25), or with the free rotation of arm (19). 51. Prisms guiding C-beam to comparator. 52, 53. These prisms are mounted so that they may be moved vertically from outside of the box until (53) intercepts the S-beam and (52) intercepts the C-beam. This operation interchanges the S- and C-beams through the sectored-disk variometer, thus greatly extending the range of this instrument.

the magnitude and uniformity of the illumination over the translucent milk-glass hemisphere. The equatorial plane of the two concentric hemispheres is a nickel-plate mirror surface (30) on a thin brass plate.

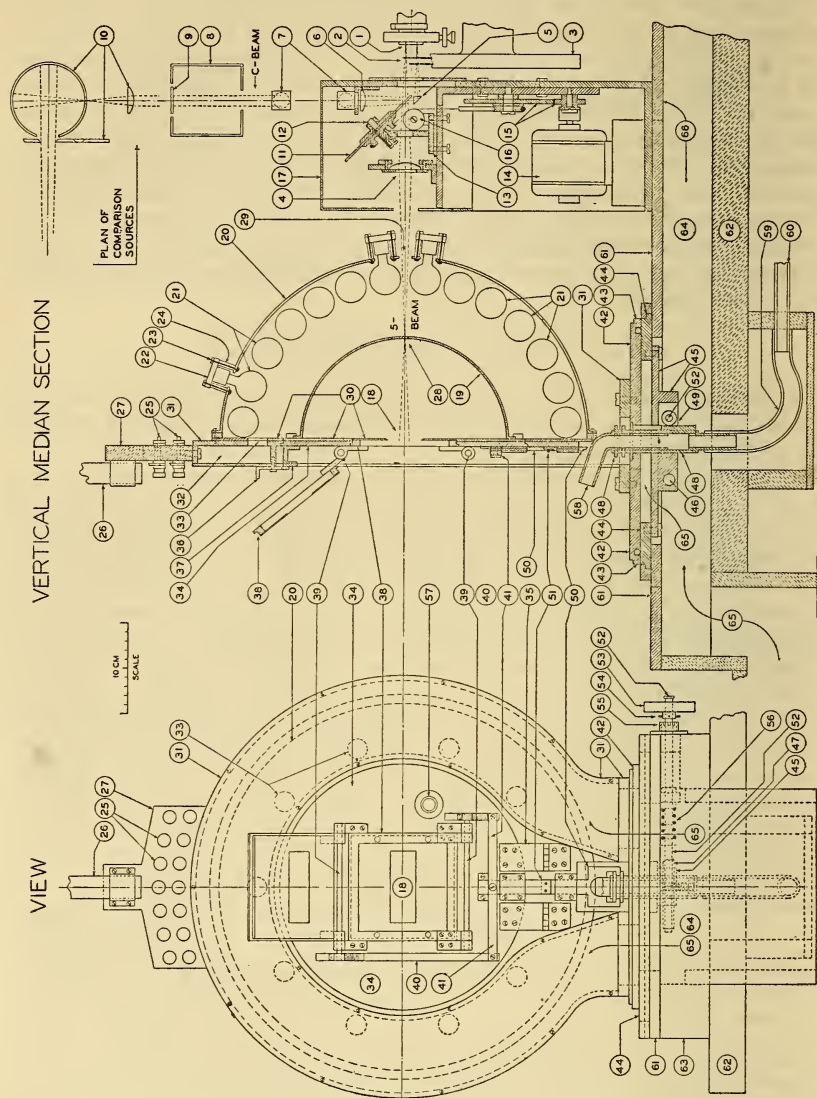


FIGURE 7.—Construction of diffused illumination unit and parts of photometric equipment. See p. 221.

A rectangular aperture (18), centered on this base, is covered by the sample or a comparison standard. Apertures of different size⁷ may be used.

⁷ The area of the illuminated portion of the sample is important. It should be large enough so that edge effects are always negligible (condition 1, sec. II), and small enough so that the reflectance of the sample has no appreciable influence on the average reflectance of the hemisphere and its base. The edge effect is the reduction in the observed brightness of the sample which is due to the uncompensated loss of light through the edges. It is only significant for thick samples of a material such as milk-glass. The average reflectance of the walls of the hemispherical inclosure determines that part of the total illumination of the sample (hence its brightness) which is due to multiple reflections within the inclosure. For a given aperture this reflectance effect is readily calculated and eliminated by a correction formula; its magnitude has been calculated for certain cases by Hardy and Pineo *J. Opt. Soc. Am.* (21, 502(1931)).

The hemisphere lamps are arranged on seven equally spaced parallels of latitude and so connected electrically that the current in each ring of lamps is independently adjustable. Some small adjustment of these currents is required to obtain the desired uniformity of brightness over the entire inner surface of the milk-glass hemisphere. Measurements of this brightness distribution, as seen from the sample, showed a residual maximum variation of about 3 percent, but the variation was less than 2 percent over the larger part of the hemisphere.

The illumination on the sample from this hemisphere source fulfills condition (4) of section II to a sufficient approximation for all diffusing media. With the lamps operating at normal voltage the brightness of a magnesium carbonate sample observed normal to its surface is approximately 6 lamberts.

The white-lined reflecting hemisphere supporting the lamps is mounted on the aluminum casting (31), with the base of the hemisphere in a vertical plane. The milk-glass hemisphere is mounted on a

1. Collimator (or entrant) slit of comparator. 2. Sected disks in light beams. 3. Sected-disk variometer. 4. Lens focusing collimator slit in plane of circular aperture (28). 5. Small total-reflection prism causing C-beam to intersect S-beam at right angles. 6. Lens controlling spread of C-beam. 7. Prism giving C-beam again a horizontal direction, so that light may be taken from comparison lamp box (8) or from inverse-square variometer (10). 8, 9. Comparison lamp box with removable portion of wall (9). 10. Parts of inverse-square variometer. See figures 2 and 10. 11. Flicker disk, 10 cm in diameter. Steel plate with two open 90° sectors. Surfaces of plate first polished and then electroplated with chromium. 12. Axle and pulley for rotation of disk. 13. Support for flicker disk, with adjusting screws for proper orientation of disk in light beams. 14, 15, 16. Motor, reducing gear, and pulleys for belt drive of flicker disk. 17. Removable cover. 18. Aperture covered by sample (or standard). The illuminated surface of sample lies 1 mm back from mirror surface. 19. Milk-glass hemisphere such as used for ceiling bowls in lighting installations. Diameter 23 cm; average thickness 2.5 mm; inner concave surface fine-ground with sand blast. 20. Steel hemisphere, spun from no. 18 gage sheet enameling stock. Diameter 40 cm; inner concave surface covered with two coats of white porcelain enamel (baked), and then "smoked" with magnesium oxide from burning magnesium shavings. 21. Gas-filled tungsten-filament lamps, 9-volt 27 cp (approximately 18 watts). Tipless spherical bulb 35 mm in diameter; candelabra screw base. First ring about pole contains 4 lamps. Other rings contain 10, 17, 23, 28, 30, and 31 lamps, respectively. Lamps connected in series-parallel arrangement and operated on 110-volt supply line. The 14 lamps in the first two rings from the pole form one of the series. Other rings are each divided into two separate series with a variable length of resistance wire in each circuit for current adjustment. 22, 23, 24. Porcelain lamp receptacle (22) is supported on hemisphere by bolts (23) passing through hemisphere and brass tubes (24). 25, 26, 27. Binding posts, wires, and hard-rubber supports for electrical connections to lamps. 28. Aperture 6 mm in diameter at pole of milk-glass hemisphere. Six similar apertures are located in the horizontal meridian plane at different angular distances from the polar axis. See text. 29. Aperture 15 mm in diameter at pole of steel hemisphere. Six similar apertures correspond in angular position to apertures (28). 30. Mirror base; nickel plating on brass. 31, 32, 33. Aluminum casting (31) forms support for hemispheres and other parts. Two flanges, with a cover plate, on the outer part of the casting forms the horse shoe-shaped compartment (32), from which air for ventilation purposes passes through holes (33) and out through annular openings around the lamp bases. 34, 35. Circular plate (34) carrying milk-glass hemisphere and other parts is mounted on hinges (35) forming door-way into outer hemispherical inclosure. 36, 37. Latch and handle for door (34). 38. Holders for sample and standard form square doors into the milk-glass hemisphere inclosure and are rigidly attached to shafts (39). 39. Shafts simultaneously rotated by rack-and-pinion arrangement, thus swinging sample or standard alternately into proper position for measurements. 40. Rectangular bars having teeth cut in upper ends. These teeth mesh with teeth in pinion wheels which are rigidly attached to shafts (39). Bars slide in shallow grooves cut in plate (34) and connect with cross bar (41). 41. Vertical motion of cross bar operates rack-and-pinion arrangement. Shifting mechanism explained below. 42. Circular brass plate with bearing on a rectangular brass plate (44). Circular plate may be rotated through 360° about a vertical axis passing through its center and lying in the illuminated plane surface of the sample. The circular plate is held in position by guides (not shown) bearing on outer edge of the plate and centered on the diagonal lines of the rectangular plate (44). There is thus no side thrust on tube (48). 43. Circular scale for reading angular position of source. 44. Rectangular brass plate carrying entire source is movable between guides in a direction perpendicular to S-beam. 45, 46, 47. The crosspiece (45) carries part of sample shifting mechanism and a hole (46) which is threaded for the large screw (47). This screw extends outside the base of the instrument and is used to effect the horizontal motion of plate (44). 48. Circular brass tubing bearing in crosspiece (45) and centered on vertical axis of rotation. The tube is movable in a vertical direction by rack-and-pinion arrangement (49), but does not rotate with the circular base plate (42). Two flanges on the upper part of the tube make sliding connection with the slide bar (50). 49. Rack-and-pinion. 50. Slide bar transmits vertical motion of tube (48) to cross bar (41), for any angular position of source. 51. Slide bar is cut and parts connected by two headless pins, thus permitting the free opening of door (34). 52. Shaft connecting pinion of (49) to handwheel (53). Pinion is keyed to shaft, and an extended keyway permits horizontal motion of plate (44), while shaft remains stationary. 53, 54, 55. Handwheel (53) is keyed to shaft (52). An extended keyway permits locking of the shaft by meshing of pins (54) with teeth (55) on shaft bearing. 56. Shaft (52) is split and connected by a heavy steel spring, permitting tension to be applied to sample shifting mechanism before locking handwheel. Sample (or standard) holder (38) is thus held firmly in position for measurement. 57. Entrance and support for high-velocity air jet, which is directed on sample for cooling purposes. 58. Brass tube freely rotating in tube (48) and connected by rubber tubing to air jet. 59. Rubber tube connection permitting free motion of sample shifting mechanism. 60. Connection to air filter. 61, 62. Main base plate and table top. 63. Square-section wood pieces raising base (61) from table top (62) to form compartment (64). 64. Compartment connected to air supply for ventilation purposes at (65). 65. Arrows show course of air between compartments (64) and (32). 66. Air stream to comparison lamp box (8). See figure 9, right-hand diagram.

circular door (34) which may be opened for inspection or renewal of the lamps, or for adjustment of the position of the milk-glass hemisphere. Figure 6 shows the opened position of the door and the arrangement of lamps on the white hemispherical background.

In the same figure a series of seven small holes in the milk-glass hemisphere may be seen extending along one meridian from the pole to the base. There are also seven corresponding but larger holes in the outer hemisphere. When the door (34) is closed the two series of holes are centered in the horizontal meridian plane common to both hemispheres, at angular distances of 0, 12.0, 25.5, 38.5, 51.0, 63.0, and 77.0°, respectively, from the polar axis. The entire hemisphere source, with the sample, is free to rotate through 360° about a vertical axis through the center of the illuminated surface of the sample. Corresponding pairs of observation holes may thus be brought in line with the stationary S-beam to the photometer and the sample observed by reflected light at the above-given angles from the normal to its surface.

The holes at the poles of each hemisphere are shown in figure 7. The conjugate focus of the entrant slit of the comparator (sec. III, 3, (a)) is formed by lens (4) approximately in the plane of the aperture in the milk-glass hemisphere. This permits the smallest possible diameter of this aperture and properly limits the observed area of the sample. This area, for observation at 0°, is semicircular in outline and approximately equal to 0.5 sq cm.

For angles greater than 90° the sample is observed by transmitted light. Because the vertical axis of rotation lies in the illuminated surface of the sample it is evident that for thick samples the observed area of the transmitting surface will be shifted appreciably for grazing angles of observation. In order to maintain the center of the observed area fixed as the source and sample are rotated about the vertical axis, the entire source may be moved by a prescribed amount between guide bars on the main base plate (61) and in a direction which is perpendicular to the fixed direction of observation. The required movement is a known function of the thickness of the sample and the angle of observation.

Thus the brightness of the sample may be observed by transmitted or by reflected light. The sample may be rotated in its own plane so that observations may be made at any desired azimuth as well as at various angles from the normal to its surfaces. Because of the symmetry of the illumination these data suffice for a complete determination of the diffusive properties of any type of material.

In the photometric procedure generally employed (described in section IV) it is necessary to bring the sample and a standard material alternately in position for measurement, and it is desirable that this operation be performed in a manner which is rapid and convenient for the observer. Furthermore, the mechanism serving this purpose must operate equally well for any given angular position of the source. These requirements are met in a satisfactory manner by the mechanism shown in figure 7 and explained in the legend. The sample holder is itself a square door into the milk-glass hemisphere inclosure, and is rigidly attached to the lower shaft (39). A similar holder for the standard is likewise attached to the upper shaft (39). These shafts are simultaneously rotated by rack-and-pinion arrangements operated

by a hand-wheel (53), which is within easy reach of the observer. As the sample holder is swung out from the base of the hemisphere, the holder carrying the standard is simultaneously lowered into place. The holders accommodate a sample 10 cm square and of varying thickness. Cross-bars with spring clips and other special devices hold the sample and standard firmly against the openings in their respective holders.

The sample need only be exposed to the radiant heat from the source during the time required for a brightness measurement. It is then swung away from the source and replaced by the comparison standard, thus having an opportunity to cool while exposed to the outer air. An additional cooling of the sample and a ventilation of the milk-glass hemisphere inclosure is provided by a high-velocity jet of air which is directed on the sample (when in position for measurement) at an angle of approximately 50° from the normal by means of a glass nozzle tube. This tube enters the hemisphere inclosure through a brass support at (57), where it is connected by rubber tubing (shown in figure 5) to the brass tube (58). This tube is free to rotate (with the hemisphere) in the stationary tube (48), which is in turn connected through an air-filter to the air supply (sec. III, 4).

The high-velocity air jet is very effective in the cooling of the surface of the sample, but the volume of air thus delivered is not sufficient for proper ventilation of the entire source. An additional forced ventilation of the outer hemisphere inclosure is necessary to carry away the large quantity of heat generated by the lamps. For this purpose a low-pressure supply of filtered air (sec. III, 4) is delivered through the opening (65) into the hollow base compartment of the instrument. The course of the air stream into the horseshoe-shaped compartment (32) is indicated by arrows (65). A section through this compartment is shown in the upper part of the figure. It extends continuously around the door carrying the milk-glass hemisphere and sample holder and through the different base plates of the instrument. From this compartment the air enters the hemisphere inclosure through nine holes (33) in the casting (31), and leaves through the many annular openings around the bases of the lamps. The air stream is thus most effective in the cooling of the lamps.

3. PHOTOMETRIC EQUIPMENT

The intensity and polarization of the S-beam, as taken from the sample under either type of illumination, is measured by direct comparison with the intensity and polarization of another beam, called the C-beam, which originates at separate constant comparison sources especially designed to accompany each illumination unit. The intensity of the C-beam may be varied in known manner until it becomes equal to that of the S-beam. The device employed for this purpose is called the variometer; that employed to bring the two beams into the proper position for direct comparison is called the comparator. The photometer is a combination of comparator and variometer with a light-sensitive receiver, which in the present equipment is the human eye. An important element of a comparator for visual photometry is the photometric field, where a criterion for the

equality of intensities of the S- and C-beams is established. In the present equipment two different criteria for this equality are provided, as employed respectively in the well-known equality-of-brightness and minimum-flicker methods of photometry.

In the equality-of-brightness method a two-part photometric field is used, one part being illuminated by the S-beam and the other part

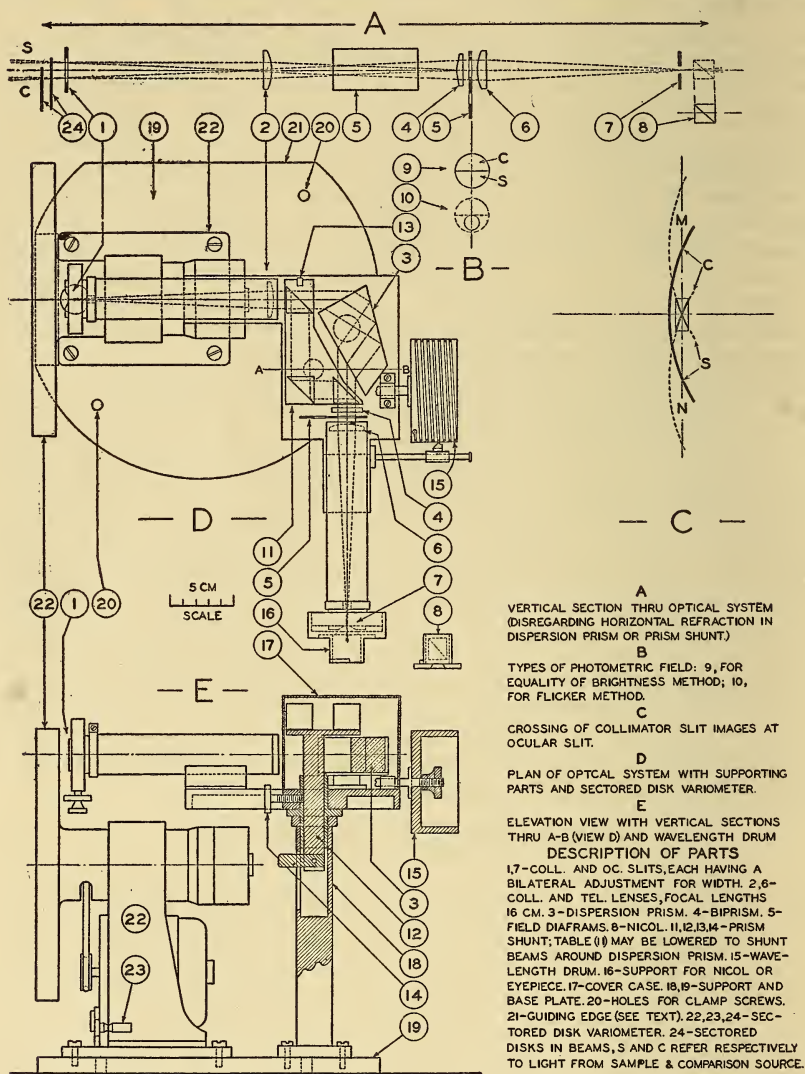


FIGURE 8.—Comparator and sectored-disk variometer.

by the C-beam. The equality of intensities is indicated by an equality of brightnesses between the two parts of the field with accompanying disappearance of the dividing line. In the minimum-flicker method a one-part photometric field is used, illuminated alternately by the S- and C-beams. The alternations cause a brightness flicker in the

field which, with proper adjustment of the frequency of the alternations, is reduced to a sharp minimum when the alternate brightnesses of the photometric field, and hence the intensities of the S- and C-beams, are the same. This provision for the use of the minimum-flicker method avoids the uncertainty of equality-of-brightness settings when the two parts of the photometric field differ in chromaticity; for, when the required flicker frequency adjustment is made the chromaticity difference disappears leaving only a residual brightness flicker.

In the present equipment the comparator is constructed to include the dispersion prism, lenses, and slit system of an ordinary spectrometer, so that beams of small wave-length extension may be filtered from the composite S- and C-beams. If the spectral filter is not required, then the dispersion prism is effectively removed by a prism shunt, and ordinary light filters may be employed to sort out desired components of the composite beams. In addition to these provisions for the control of spectral conditions, a nicol prism may be employed to separate like polar components from each beam. This provision is required in polarization measurements and in some intensity measurements. Detailed description of the photometric equipment is given in the following sections:

(a) COMPARATOR AND SELECTIVE LIGHT FILTERS

The passage of the S- and C-beams through the optical parts of the comparator is shown in views A and D of figure 8. The instrument is essentially a spectrometer equipped with a constant deviation dispersion prism (3) and a prism shunt (11, 12, 13, 14). A biprism (4) mounted over the telescope lens (6) is the essential element added to the original instrument to convert the device into a comparator.⁸

The dispersion system of the instrument (parts 1, 2, 3, 6, and 7) selects any desired homogeneous component from the composite entrant beams. When the diffusive and absorptive properties of the sample are to be measured directly for some fixed condition of composite illumination (table 1), the dispersion prism is effectively removed from the optical system by insertion of the prism shunt, which is shown in views D and E of figure 8. By loosening set screw (14) the circular plunger (12) may be lowered until the three total-reflection prisms on table (11) intercept the beams emerging from lens (2) and direct them around the dispersion prism to the biprism. A vertical guide bar (13) prevents any rotation of the prism table. The prisms are readily adjusted so that this change is made without appreciable shifting of the paths of the entrant beams. When the prism shunt is used light passes through the instrument with but slight alteration in spectral distribution. Suitable glass or liquid light filters may be inserted in the beams at any convenient position before the eye. This completes the arrangements for effective control of the spectral conditions of illumination on the sample.

By inserting a nicol prism before the emergent slit of the comparator only the corresponding polar component of each entrant beam eventually reaches the eye. The nicol is mounted in a cylindrical tube (8) which may be inserted in the projecting tube (16). A pin on the

⁸ This form of biprism spectrocomparator, when used with the sector-disk variometer (22, figure 8), is essentially the arrangement employed in the Keuffel and Esser spectrophotometer. See C. W. Keuffel *J. Opt. Soc. Am. & Rev. Sci. Instr.* **11**, 403 (1925).

nicol tube fits a slot in the holder tube so that the principal plane of the nicol may be oriented accurately in vertical and horizontal positions. Hence measurements of the polarization of the S-beam are made only with reference to vertical or horizontal planes. For a majority of the measurements on different samples the vertical reference plane will be perpendicular to the plane of incidence for unidirectional illumination, and always perpendicular to the plane of observation with the hemisphere source. Generally the vertical or horizontal plane will be the principal plane of polarization for the S-beam. This is not always the case, however, particularly for materials such as textile fabrics having structural features varying with direction on the surface.

Upon looking through the emergent (or ocular) slit (7) of the comparator one sees the uniformly illuminated surfaces of the biprism. The field of view, called the photometric field, is limited by the form and size of the diaphragm aperture (5). In the equality-of-brightness method of photometry a large circular aperture is used which exposes equal areas of each inclined face of the biprism, as shown at (9) in view B, and subtends an angle of approximately 5.5 degrees at the ocular slit. The photometric field is thus divided into two equal semi-circular parts by the sharp horizontal line of intersection of the biprism faces. The two entrant beams pass, respectively, one through each inclined face of the biprism and thence through the emergent slit (and nicol) to the eye. In the minimum-flicker method of photometry the one-part photometric field is limited by a small circular aperture, which is shown at (10) in view B and subtends an angle of 2 degrees at the ocular slit. This aperture is eccentric with respect to the axis of the lens system and exposes to view only a part of one face of the biprism. The paths of the S- and C-beams must therefore be exactly superposed in their passage through the instrument. Optical arrangements for this purpose are described in (sec. 3 (d)).

The brightnesses of the adjacent parts of the photometric field in the one method, or the alternate brightnesses of the same part of the field in the other method, are proportional respectively to the intensities of the corresponding entrant beams, or to the particular homogeneous, composite, or polar components of the beams which are being transmitted by the comparator to the eye. In both methods the intensity of the C-beam relative to that of the S-beam, is controlled by the variometers described below, until the respective criterion for equal field brightnesses is satisfied. The intensity ratio is then given by the variometer reading, with due regard to the polarization of the entrant beams as considered in section IV.

The comparator is mounted on the base plate (19), along with the sector-disk variometer (sec. 3 (b)), so that the combination may be transferred readily from one illumination unit to the other. It is shown in proper position with each unit in figures 3, 4, and 5. The exact position of the photometric unit in the base plates of either illumination unit is determined by the straight edge (21), figure 8,

which is pushed snugly against a corresponding edge on the base plate of each illumination unit. The exact position of the instrument parallel to this edge, which is parallel to the paths of the entrant beams, is relatively unimportant.

(b) SECTORED-DISK VARIOMETER

The sector-disk variometer⁹ is a combination of two sector-disk, each with two 90° apertures, and rotating in the same direction with equal angular velocity. One of these disks is larger in diameter than the other and cuts the S- and C- beams, as illustrated at (24) in figure 8. The other disk cuts the C-beam only. The phase angle between the rotating disks may be varied continuously so that the ratio of the total aperture of the combination of disks to the aperture of the single outer disk varies continuously from zero to unity, with a corresponding continuous variation in the relative (time-averaged) intensities of the entrant beams. The intensity ratio is read directly on the instrument scale.

The device is mounted so that both disks may be lowered slightly until the two disks cut the C-beam only. This operation doubles the scale reading of the instrument and doubles the field brightness in the comparator corresponding to a given intensity of the S-beam. The transmission range of the instrument now extends from 0 to 0.5, but the greater field brightness and more open scale are advantageous in the measurement of low intensities.

(c) COMPARISON SOURCES

Upon reference to the general plan of the equipment in figure 2, it is seen that the C-beam is taken from the interior surface of either of two lamp inclosures (designated as comparison sources), depending on the particular illumination unit with which the comparator is being used. In either case the observed portion of the interior surface is removable, permitting the C-beam to be taken instead from the interior surface of a hollow sphere. This sphere is part of the inverse-square variometer (sec. 3 (e)).

The right-hand diagram in figure 9 shows the construction of the comparison lamp inclosure used with the diffused illumination unit. With the lamps operating at normal voltage the brightness of the interior surface is approximately the same as the interior brightness of the milk-glass hemisphere. Hence the brightness of this comparison source is always equal to or greater than the brightness of a sample under the hemisphere illumination. The left-hand diagram in figure 9 shows the construction of the comparison lamp inclosure used with the unidirectional illumination unit.

The construction principle for both of the comparison sources is the same. The lamps are placed in a small inclosure with walls of

⁹ See detailed description of similar instruments by C. W. Keuffel, *J. Opt. Soc. Am. and Rev. Sci. Instr.* 11, 403(1925).

high reflectance and good diffusing power. Hence, the greater part of the illumination of the interior wall is the diffused light multiply

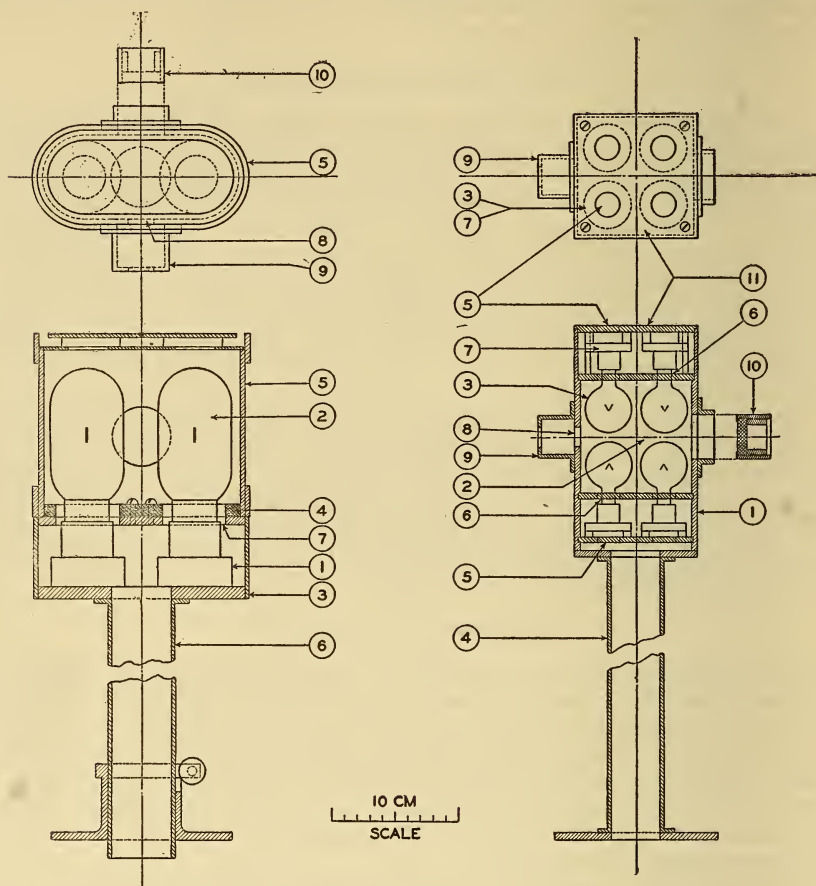


FIGURE 9.—Construction of comparison sources

A.—Right-hand source used with diffused illumination unit.

1. Aluminum box. 2, 3. Cubical compartment containing bulbs of 8 lamps of same type as hemisphere lamps, figure 7. Interior surface of compartment heavily coated with magnesium oxide. 4, 5. Brass tube support and holes through which a forced draft of air is supplied for ventilation. 6. Bases of lamps project through circular holes in top and bottom of cubical compartment. Annular openings about lamp bases serve for ventilation purposes. 7. Lamp receptacles. 8, 9. Apertures for C-beam to comparator. 10. Removable circular portion of back wall, from which C-beam to comparator is taken. 11. Top of box, with upper 4 lamps, is removable for inspection or renewal of lamps.

B.—Left-hand source used with unidirectional illumination unit.

1. Mogul lamp receptacle. Upper portion of porcelain body cut away for better cooling of lamp base. 2. Lamp units up to 1,000 watts may be used. 3. Support for lamps receptacles. 4. Asbestos plate. Upper surface smoked with magnesium oxide. 5. Sheet-iron shell with removable top. Inner surfaces coated with white porcelain enamel and smoked with magnesium oxide. Shell fits snugly over asbestos plate and is readily removed for renewal of lamps. 6. Supporting brass tube through which a forced draft of air is supplied for cooling purposes. 7. Annular opening about base of lamp for ingress of air to lamp inclosure. 8, 9. Apertures in front wall of lamp inclosure for passage of C-beam to comparator. 10. Removable circular portion of the back wall, from which the C-beam to comparator is taken.

reflected within the inclosure. The lamps are symmetrically arranged with respect to the emergent C-beam. Thus a source of

uniform brightness over an extended area is obtained with no appreciable polarization of the C-beam to the comparator. Moreover, small lateral displacements of this beam do not appreciably alter its intensity.

(d) FLICKER-DISK ATTACHMENTS

In the use of the minimum-flicker method of photometry, provision must be made for a rapid periodic substitution of the C-beam for the S-beam in the comparator. This substitution is effected with the flicker-disk attachments which form accessory parts of each illumination unit.

By reference to figure 7 it is seen that the path of the S-beam is direct and horizontal from the sample to the entrant slit of the comparator. The path of the C-beam from the comparison sources is turned downward at prism (7) and intersects the path of the S-beam at 90° . A polished metal disk with two 90° open sectors is placed at the intersection of the beams so that the upper mirror surface of the disk contains the point of intersection of the axes of the beams and is inclined at 45° to each axis. By rotation of the disk the C-beam is periodically substituted for the S-beam whenever a closed sector of the disk intersects the beams.

By reference to the unidirectional illumination unit in figure 4, the paths of the S- and C-beams from the sample and comparison sources may be followed. A small flicker disk (47) is inserted at the intersection of the beams in a manner similar to that described for the diffused illumination unit. The principle of operation is precisely the same as before.

When the minimum-flicker method is used the diaphragm slide (5) of figure 8 is moved so that the field of view is limited by the circular aperture (10), and the sectored-disk variometer (22, 24) is set with open sectors permitting free passage of the beams to the comparator. The equality of intensities is effected by use of the inverse-square variometer.

(e) INVERSE-SQUARE VARIOMETER

In the minimum-flicker method of photometry a sectored-disk variometer is inapplicable because of the obvious introduction of stroboscopic effects. The variometer commonly employed in this case is based on the inverse-square law of photometry, and consists essentially of a lamp suitably mounted on a track so that its distance from a diffusion screen may be varied continuously. Assuming that certain conditions, considered below, are fulfilled to a sufficient approximation, then the brightness of the diffusion screen, by reflected or transmitted light, is proportional to the inverse square of the distance between the lamp and the screen. The screen thus serves as a continuously variable secondary source of light for the comparison beam to the photometer.

The inverse-square variometer used with the present equipment is outlined in figure 2. Two spherical diffusion screens are provided, each formed by the interior surface of a hollow white-lined sphere. The spheres are placed one at each end of the lamp track, and each sphere serves as a variable comparison source for separate use with

the flicker-disk attachment of the corresponding illumination unit. Inasmuch as the construction of both ends of the variometer is the same, only one end of the instrument is shown in figure 10. The C-beam is taken from the interior magnesium-oxide surface of the sphere (3). Lamp (8) is movable along track (11) and its light

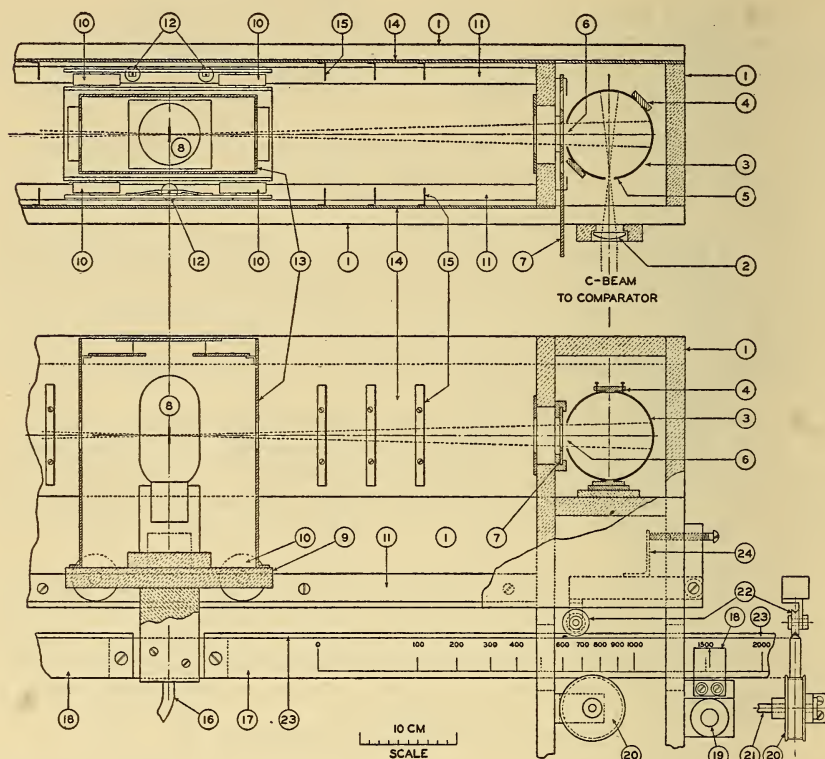


FIGURE 10.—Construction of inverse-square variometer.

1. Wood frame. 2. Lens (with lens 6 of figure 7) focusing comparator slit approximately in plane of aperture in sphere (3), thus permitting use of small aperture. 3. 4. Iron sphere 95 mm in diameter, built up of two hemispheres and a supporting iron ring (4). Inner surface of sphere coated with white porcelain enamel and smoked with magnesium oxide. 5. Aperture for C-beam, diameter 6 mm. 6. Aperture for entrant beam to sphere, diameter 22 mm. 7. Brass slide having three apertures of different diameter, any one of which may be placed before sphere aperture (22). Areas of apertures are in the proportion of 10:5:1. 8. 400-watt projection lamp, with plane of lamp filaments parallel to plane of aperture into sphere. 9. Lamp carriage. 10. Roller skate wheels. 11. Track for lamp carriage made of one-inch angle iron and screwed to sides of wood frame. 12. Small wheels rolling against vertical side of angle-iron track, thus preventing the scraping of carriage against side of track. 13. Lamp box. 14, 15. Blackened metal fins preventing reflection of light from sides of frame into sphere. 16. Flexible current leads. 17. Seasoned wood driving bar attached to lamp carriage. Heavy white paper is glued to sides of bar and one side ruled with a distance-squared scale. 18, 19. Pointer and lamp for reading scale. 20. Rubber-tired drive-wheel for bar (17). 21. Shaft connecting drive wheel with hand wheel, which is placed within convenient reach of observer. 22. Guiding pulley rolling on angle brass strip (23). 23. Angle brass strip screwed to upper flat edge of (17), thus guiding motion of bar. 24. Spring brass providing downward tension on (22).

admitted to the sphere through any one of three circular apertures in slide (7). The largest aperture is 20 mm in diameter and the areas of the three apertures are in the proportion of 10:5:1. These apertures are made accurately and calibrated mechanically.

The intensity of the C-beam to the comparator is proportional to the total quantity of light projected into the sphere, which in turn is proportional to the area of the effective entrant aperture and to the

inverse square of the distance between the plane of the lamp filaments and the plane of the aperture. The accuracy of this law for the lamp track and spherical diffusion screen was tested¹⁰ by comparison with the scale of the sectored-disk variometer, which had been calibrated previously by use of standard sectored disks of accurately known aperture. It was found that for each aperture into the sphere, and for lamp positions down to 15 cm from the aperture, no departure from the inverse-square law was indicated by the photometric measurements, the uncertainty of which is estimated as 1.5 percent. Also, when the three different apertures were used successively, with the lamp fixed at distances of 50 and 20 cm from the sphere, the relative intensities of the C-beam were in each case with the same degree of accuracy in the proportion of 10:5:1.

The spherical diffusion screen, with its variable entrant aperture, affords a convenient and accurate means for extending the intensity range of the lamp track. The arrangement replaces the plane reflection or transmission types of diffusion screen and the approximately neutral light filters commonly employed in this type of variometer. The apertures are, of course, strictly nonselective in their spectral transmission, so that the relative spectral distribution of light in the C-beam remains constant over the entire intensity range of the variometer. This is a very desirable feature of the instrument.

Another reason for the use of this type of diffusion screen with the present equipment is that an extended source of the highest possible brightness is desired with no polarization in the C-beam to the comparator. The spherical screen fully fulfills the polarization condition, the advantage of which is explained in section IV. A plane magnesium carbonate reflection screen would yield a comparable intensity of the C-beam but then the beam would be partially polarized. The polarization condition could be fulfilled with a plane transmission screen such as milk-glass; but, if this screen is a sufficiently good diffusor so that the inverse-square law of the instrument is accurate,¹¹ then its transmission is likely to be so low that the spherical screen gains the intensity advantage. A thorough quantitative investigation of this point has not been made. It is possible that entrant apertures of larger diameter could be used with the sphere, thus increasing the collection of light from the lamp.

4. VENTILATION SYSTEM

Of the five different light sources provided with this equipment, the track lamp (8, fig. 10) is self-ventilating, and a forced ventilation has been described for the unidirectional illumination source. The hemisphere source for completely diffused illumination, and the two comparison sources (fig. 9), each contain lamps in an inclosure, the interior surface of which is coated with magnesium oxide.

¹⁰ For this test the S-beam to the comparator was taken from a magnesium carbonate surface illuminated by a 400-watt lamp. This lamp was operated in series with the 400-watt track lamp, and the current held constant during the test. The relative intensities of the C-beam for different positions of the track lamp could then be measured with the sectored-disk variometer and the result compared with values computed by the inverse-square law.

¹¹ The diffusion screen of whatever type must be a sufficient approximation to the ideal perfect diffusor that the intensity-direction gradient in the neighborhood of the mean direction of observation remains sensibly constant as the distance of the lamp from the screen is changed. The permissible degree of departure of the screen from the perfect diffusor depends on the degree of approximation of the illumination on the screen to the ideal unidirectional condition. It is of interest to note that the perfect diffusor and strictly unidirectional illumination are both ideal concepts which can be approached without limit but are never exactly realized. Consequently, the law of the inverse-square variometer can be made to operate to any desired degree of accuracy by proper choice of above-mentioned conditions.

It has been found necessary to filter the air used for the ventilation of such inclosures in order to remove dust and dirt which otherwise would be deposited on the white reflecting surfaces and thus appreciably reduce their reflectance. This is particularly undesirable in the hemisphere source, for the uniformity and constancy of the reflectance over the surfaces is of importance in maintaining the desired condition of illumination on the sample. Likewise, air used for direct cooling of the sample in the diffused-illumination unit must be cleaned before being used in order to prevent the deposition of dirt on the sample or standard.

The construction of air filters and their connection to the light sources is clearly depicted in figure 11. Each filter consists of a few overlapping layers of absorbent cotton, held in place between two wood frames, which are covered with coarse-mesh wire screening. The high-velocity air jet for cooling the sample (see parts 57, 58, 59,

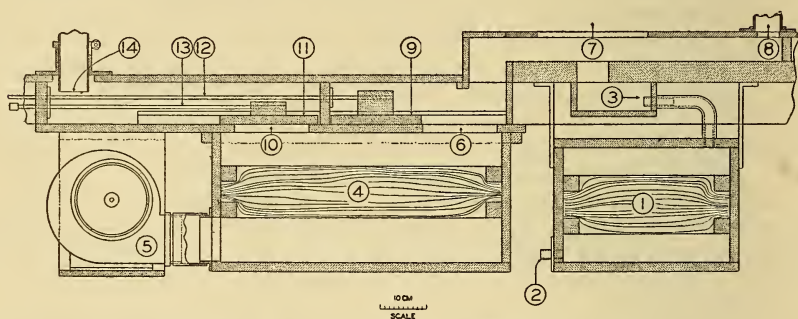


FIGURE 11.—Construction of ventilation system

1. Air filter consisting of three or four layers of absorbent cotton. 2. High-pressure air inlet. 3. Connection to diffused illumination unit for high-velocity air jet on sample. (See fig. 7, pts. (59) and (60).) 4. Air filter for low-pressure large-volume supply to hemisphere (fig. 7) and to comparison lamp sources (fig. 9). 5. Blower. 6. Outlet to (7) and (8). 7. Air passage to hemisphere source. Connects with compartment (32) of figure 7. 8. Air passage to comparison source for diffused illumination unit. See arrow (66) of figure 7 and right-hand diagram of figure 9. 9. Sliding door to close passage (6). 10, 11. Sliding door to open passage (10) when air supply is needed for ventilation of comparison source used with unidirectional illumination unit. See left-hand diagram of figure 9. 12, 13. Rods to operate doors (9) and (11). 14. Air passage to comparison source. See figure 9, left, part (6).

and 60, figure 7) is supplied through filter (1), figure 11, from the laboratory compressed air supply. A larger volume of air at lower pressure is supplied by the blower (5) through the larger filter (4). This serves for the ventilation of the hemisphere and comparison sources.

IV. INTENSITY AND POLARIZATION MEASUREMENTS

In the preceding description of the equipment and its operation a given homogeneous, composite, or polar component of the S-beam is always compared directly with a corresponding or a fixed component of the C-beam, the intensity of which can be varied in a definitely determined manner. The suggested procedure in the measurements would imply that the absolute intensity of any component of the C-beam is known in terms of some fixed intensity unit. This is not the case, however, and hence it is necessary to apply a substitution method as the standard photometric procedure in intensity measurements.

In the substitution method the intensity of the S-beam with the sample in place is compared with the intensity of the S-beam from a standard material, when the standard is subjected either to the same conditions of illumination as the sample or to some other definitely specified conditions. If the diffusive and absorptive properties of the standard are known, then the corresponding properties of the sample are determined. In the application of the method the standard is alternately substituted for the sample and each compared successively with the comparison source, so that the C-beam thus serves only as a means for balancing intensities of the S-beam from sample and standard, respectively, and the properties of the comparison sources are thus eliminated from the final results of the measurements.

Under various conditions of illumination many materials introduce a considerable degree of polarization in the light reflected or transmitted to the photometer. In the general photometric procedure to be described it is assumed at first that the polarizing properties of

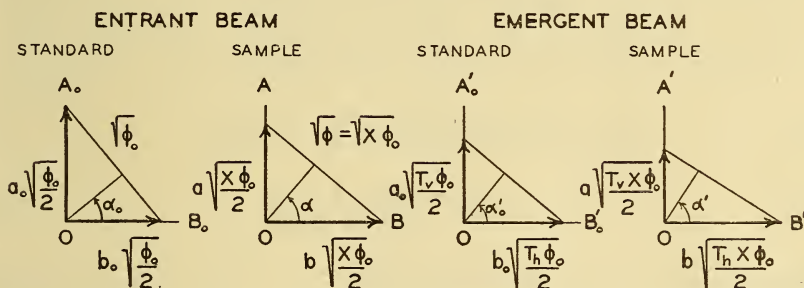


FIGURE 12.—Polar analysis of light beams, before and after passage through the comparator

$\phi \equiv$ intensity; $P \equiv$ polarization; $a^2 + b^2 = 2$. $P \equiv \frac{[(OA)^2 - (OB)^2] + [(OA)^2 + (OB)^2]}{2} = 0.5 (a^2 - b^2) = \cos 2 \alpha$.
 $a^2 = 1 + P$; $b^2 = 1 - P$; $-1 \leq P \leq 1$

the sample are to be measured along with the spectral or directional intensity distributions of reflected or transmitted light. The discussion will apply equally well to the measurement of homogeneous or composite components of the S-beam and in the use of either type of variometer in either the equality-of-brightness or minimum-flicker methods of photometry. The polarization of the S-beam is herein measured with reference to a vertical plane. This reference plane is most significant in a later discussion of polarization errors and will be approximately coincident with, or perpendicular to, the principal plane of polarization of the S-beam for the majority of measurements that may be required in various applications of the equipment.

Let Φ_0 and P_0 represent, respectively, the intensity and polarization of the S-beam, when this beam is taken from the surface of the standard. Let $X\Phi_0$ and P represent the corresponding quantities when the sample is substituted for the standard. The factor X is the brightness ratio of sample to standard and is the quantity to be derived from the variometer readings. The polar analysis of the S-beam, as taken from the sample or standard, is given in the left half of figure 12. The vertical and horizontal vectors represent, respectively, the amplitudes of the vertical and horizontal polar components of intensity.

Let T_v and T_h represent, respectively, the transmissions of the comparator for the vertical and horizontal polar components of the S-beam. All factors determining the transmission of the instrument affect the two components equally, with the exception of reflection phenomena at the surfaces of the dispersion prism. As described by the Fresnel reflection laws the horizontal polar component at these surfaces is more copiously transmitted than the vertical component. The polar analysis of the S-beam after emergence from the ocular slit of the comparator is represented in the right half of figure 12. When the principal plane of the nicol is set vertical or horizontal, then only the corresponding polar component of the S-beam is transmitted through this prism to the eye.

Let X'_v be the ratio of variometer readings for the vertical polar components of the S-beam, as received from the sample and standard, respectively. Let X'_h denote the corresponding ratio for the horizontal polar components. Then, by figure 12,

$$X'_v = X \cdot \frac{a^2}{a_o^2} = X \cdot \frac{1+P}{1+P_o} \quad (1)$$

$$X'_h = X \cdot \frac{b^2}{b_o^2} = X \cdot \frac{1-P}{1-P_o} \quad (2)$$

Let
$$X' \equiv \frac{X'_v + X'_h}{2} = X \cdot \frac{1-PP_o}{1-P_o^2} \quad (3)$$

and
$$P' \equiv \frac{X'_v - X'_h}{X'_v + X'_h} = \frac{P - P_o}{1 - PP_o} \quad (4)$$

Then
$$X = X' \cdot \frac{1 - P_o^2}{1 - PP_o} \quad (5)$$

$$P = \frac{P' + P_o}{1 + P_o P'} \quad (6)$$

These formulae show how, in the substitution method, the polarizing properties of the sample and standard enter into the required intensity and polarization measurements. The same formulae will apply, of course, when the substitution method is not employed, for then the C-beam would take the place of the S-beam from the standard, and P_o would represent the initial polarization of the C-beam. It is more convenient when only polarization, or only relative directional distributions of light are measured, to eliminate the use of the standard and to employ the more direct comparison method of photometry. It is for this purpose that care was taken in the design of all comparison sources to have the initial polarization of the C-beam zero. Likewise, in the use of the substitution method, it is important to choose experimental conditions such that the initial polarization P_o of the S-beam from the standard is negligible. Then, directly, $X=X'$, and $P=P'$. To fulfill this condition a uniform and optically isotropic diffusing medium is chosen for the standard. Under completely diffused illumination it may always be observed normal to its surfaces for reflected or transmitted light. Under unidirectional normal illumination it may also be observed

normal to its surfaces by transmitted light. Under such symmetrical conditions of illumination and observation the polarization, P_o , will be negligible or zero.

It is seen that the general photometric procedure in the intensity or polarization measurements calls for separate measurements of mutually perpendicular polar components and the combination of such measurements in equations (3), (4), (5), and (6). In the majority of the applications of this equipment, however, a determination of the polarizing properties of materials is not required. In such event the intensity measurements may be simplified by direct measurement of the whole intensity of the S-beam (nicol removed), provided certain additional conditions are fulfilled. In consequence of the polarizing action of the dispersion prism the transmission of the comparator depends on the state of polarization of the entrant beams, and appreciable errors in the intensity measurements may result if the variable polarization of the S-beam is disregarded.

Let it be assumed that the nicol is removed from the optical system of the comparator so that the whole intensity of the S-beam, unresolved into polar components, is to be measured directly by either of the photometric methods provided. Let X' represent, as before, the ratio of variometer readings. Then, by reference to figure 12, we have

$$X' = X \frac{(a^2 T_v + b^2 T_h)}{(a_o^2 T_v + b_o^2 T_h)} = X \cdot \frac{1 + PP_i}{1 + P_o P_i}$$

or

$$X = X' \frac{1 + P_o P_i}{1 + PP_i} \quad (7)$$

where $P_i = \frac{T_v - T_h}{T_v + T_h}$ is the polarization introduced by transmission of light through the comparator with dispersion prism.

Let ΔX be the difference between the true brightness ratio X and the value X' given by the variometer readings. Then the fractional error in the brightness ratio, which would result if the polarization of the beams were disregarded, is

$$\frac{\Delta X}{X} = \frac{X' - X}{X} = \frac{(P - P_o) P_i}{1 + P_o P_i} \quad (8)$$

It is seen that there are two conditions for which the error is zero. The polarization P_i is practically all introduced by the dispersion prism of the comparator; hence in all nonspectral measurements, wherein the prism shunt is used, $P_i = 0$ and the polarization error is zero. Likewise, when the polarization of the beams from the sample and standard are the same, then $P = P_o$.

When the conditions of measurement are chosen such that the polarization of the beam from the standard is always zero, then $P_o = 0$ and $X = X'/(1 + PP_i)$, so that

$$\frac{\Delta X}{X} = PP_i \quad (9)$$

Having the refractive index of the dispersion prism material for different wave lengths, the spectral transmission of the prism (disregarding

absorption in the prism glass) has been computed by means of the Fresnel formulae for the vertical and horizontal polar components of the entrant beams. These components are perpendicular and parallel, respectively, to the plane of incidence on the dispersion prism. From the values of T_v and T_h thus obtained, the fractional polarization P_i was computed. The data are shown in table 2.

TABLE 2.—*Polarization introduced by the dispersion prism*

Wave length (m μ)	Transmission of prism by Fresnel formulas		Polarization P_i	Wave length (m μ)	Transmission of prism by Fresnel formulas		Polarization P_i
	T_h	T_v			T_h	T_v	
420.....	0.9947	0.5317	−0.365	580.....	0.9993	0.4748	0.312
460.....	.9971	.5104	.344	620.....	.9995	.4678	.306
500.....	.9983	.4951	.330	660.....	.9998	.4621	.301
540.....	.9990	.4840	.320	700.....	.9999	.4576	.297

It is seen that the mean value of P_i throughout the spectrum is approximately -0.32 . Thus a 31 percent polarization of the S-beam from the sample would result in an error of 10 percent in the direct measurement of the brightness ratio X of sample to standard.

In the usual methods of spectrophotometry the sample and standard are observed simultaneously under equal illumination from the same source and the C-beam is taken directly from the surface of the standard. The above analysis applies identically to this case and P_o is then the polarization of the C-beam.

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